

DRAG REDUCTION USING HIGH MOLECULAR WEIGHT POLYMERS IN TAYLOR-COUETTE FLOW

PALLAVI BHAMBRI & BRIAN FLECK

Department of Mechanical Engineering, University of Alberta, Edmonton, Canada

ABSTRACT

Turbulent drag reduction with high molecular weight polymers is examined experimentally using Taylor-Couette (TC) flow set-up. The set-up consisted of a rotating inner cylinder and a static outer cylinder with radius ratio (η) = 0.76 and aspect ratio (Γ) = 10.57. A reaction torque sensor was used to measure the torque acting on the inner cylinder. Experiments were conducted on a wide range of Reynolds numbers varying from 50,000 to 280,000 and the dimensionless torque (G) was used to scale the torque which compared well with the previous TC studies. For drag reduction, four different concentrations i.e. 80, 120, 160 & 200 PPM of polyacrylamide/ Drag Reducing Agent (DRA) solutions were used. The skin friction coefficient (c_f) was used to infer the drag reduction in the experiments. The effect of concentration and Re on Drag Reduction was investigated. A maximum drag reduction of 63% was observed for 160 PPM solution. The TC set up is a suitable configuration for drag reduction testing and is more convenient than channel flow set up. The results were found to scale well with the turbulent drag in wall bounded shear flows (such as pipe/channel flow).

KEYWORDS: Drag Reduction, Taylor-Couette Flow, Turbulent Flow, Skin Friction Coefficient, Polymer

Received: Jan 30, 2016; **Accepted:** Feb 04, 2016; **Published:** Feb 09, 2016; **Paper Id.:** IJMPERDFEB20167

INTRODUCTION

Significant amount of power is depleted in pumping the fluids to overcome the pressure drop in pipelines. Substantial research has been intensively carried out to decrease this loss by either modifying the pipe inner surface or using some additives in the fluid. Reductions in pressure drop, or in other words drag reduction using high molecular weight polymers (known as Drag Reducing Agents (DRA)), is well recognized because simply by the addition of small concentration of DRAs, drag can be significantly reduced (up to 70%) leading to substantial energy savings (Ptasinski et al. 2001). After it was revealed by Toms (1949), this phenomenon has gathered enormous attention because of its practical application in pipelines. Virk et al. (1967, 1969) studied the onset of polymer drag reduction and demonstrated that there is a critical value of Reynolds number required (i.e. 12000) for drag reduction to occur. Drag reduction doesn't take place in laminar flow and the polymer helps in reducing the drag only after a certain value of wall shear stress (which is equal to 7 Pa for Polyethylene oxide).

Since turbulent flow is easily achievable in pipe flow, the majority of the experimental investigations in this area are conducted in either channel or pipe flow (Hershey & Zakin 1967; Lumley 1969; White et al. 2004). Further, drag reduction in such a setup can be easily inferred from pressure drop at a constant flowrate. However, a significant amount of drag reducing agents are required for conducting tests at lab scale; making it an expensive process. In order to overcome this limitation, a Taylor Couette (TC) Flow setup has been utilized in this study to examine the commercially available polymers for drag reduction and to prove that turbulent Taylor-Couette testing

is a convenient and cost effective analogue for pipe flow drag reduction. In addition, high Reynolds number and high wall shear stress can be easily accomplished in this setup.

Taylor-Couette flow is an instability in fluid flow arising in between two differentially rotating concentric cylinders. Because of its convenient geometry, it is widely used to study the instability and pattern formulation in turbulence at a small scale (Cole 1976; Davey 1962; Lewis & Swinney 1999). It is a closed system and possesses a simple geometry permitting a well-defined energy balance. A TC setup can be of three types: a) rotating inner cylinder, b) rotating outer cylinder and c) rotating both inner and outer cylinder.

The following parameters describe a Taylor Couette System: r_i is inner cylinder radius, r_o is the outer cylinder radius, Ω_i is inner cylinder angular velocity, Ω_o is outer cylinder angular velocity, L is the length of inner cylinder, ν is fluid kinematic viscosity and ρ is the fluid density.

$$\eta = r_i / r_o \quad (1)$$

$$Re = (\Omega_i r_i (r_o - r_i)) / \nu \quad (2)$$

$$Re_o = (\Omega_o r_o (r_o - r_i)) / \nu \quad (3)$$

$$d = r_o - r_i \quad (4)$$

$$\Gamma = L / d \quad (5)$$

Where η is the radius ratio, Re is the inner cylinder Reynolds number, Re_o is the outer cylinder Reynolds number, d is the annular gap and Γ is the aspect ratio.

The described set-up was first utilized by Couette (1890) to measure viscosity and consisted of a rotating outer cylinder and a static inner cylinder. Two different regimes i.e. laminar and turbulent were studied. A later study was done by Taylor (1923) who examined flow in concentric cylinders (inner rotating cylinder) experimentally as well as numerically. Critical Reynolds number required to obtain the instability in fluid flow in this system was experimentally observed and numerically proven through his work. Wendt (1933) for the first time provided an extra dimension to this setup by studying TC flow with two independently rotating cylinders which easily enables the set up to reach highly turbulent regime. Torque was measured at different Reynolds number at several radius ratio of the setup.

Centrifugal instability is the reason for the development of Taylor vortices at low Re in this setup (Di Prima and Swinney, 1985). With increasing Re , classical regime is obtained in which boundary layers are of laminar type however turbulence is developed in the bulk at length scales between the Kolmogorov and the integral scale. Further increasing the Re , leads to development of the ultimate turbulent regime in the system which consists of turbulent boundary layers (Huisman et al. 2013). Lathrop et al. (1992) observed that behavior of torque in TC flow, at such a large Re , is consistent with the turbulent drag in wall bounded shear flows such as turbulent channel/pipe flow. It was postulated that turbulent TC flow wall turbulence is similar to Boundary layer wall turbulence.

Lathrop et al. (1992) considered the core region as an extension of turbulent boundary layers and assumed logarithmic boundary layer at the wall. Whereas, Panton (1992) supposed constant angular momentum in the core. Both the authors arrived at a similar analytical solution using G and Re . Lathrop et al. (1992) equated Prandtl expression for turbulent shear stress with $T/(rA)$ where T is the Torque and A is the area of cylindrical fluid element at radius r . The final expression obtained was

$$\frac{Re}{\sqrt{G}} = N \log_{10} \sqrt{G} + M \quad (6)$$

$$\text{Where } N = \frac{(1-\eta^2) \ln 10}{\eta \kappa \sqrt{2\pi}} \quad (7)$$

$$M = N \left[\ln \left\{ \left(\frac{1-\eta}{1+\eta} \right) \frac{1}{y_0^+ \sqrt{2\pi}} \right\} + \kappa y_0^+ \right] \quad (8)$$

Here κ is the *von-Kármán constant* and y_0^+ is the dimensionless distance from the wall stated in Law of the wall. Skin friction coefficient (c_f) is given by Equation 9, where τ_w is wall shear stress.

$$c_f = G/Re^2 = 2\pi r_o^2 \tau_w / \rho v^2 Re^2 \quad (9)$$

The final expression is obtained as

$$\frac{1}{\sqrt{c_f}} = N \log_{10} (Re \sqrt{c_f}) + M \quad (5.10)$$

Following this, intensive research has been carried out in this region and several areas such as rise of instabilities with changing Reynolds number, pattern formation using flow visualization; end wall effects have been explored both experimentally as well as numerically (Merbold & Egbers 2012; Poncet et al 2013; Abshagen 1997). Experiments in the area of torque scaling at reasonably high Reynolds number have been demonstrated recently where dimensionless torque ($G = T / (L\rho v^2)$) is used for scaling the torque (Lathrop 1992; Van Gils et al. 2011).

The TC system has been studied in the past for drag reduction using additives and surface modification. Yi and Kim (1997) experimentally studied the stability of TC flow with drag reducing solutions to investigate the effect of polymers on high molecular weight polymers. Increase in critical Reynolds number with addition of polymer was observed, however, drag reduction was not quantified in this study. Kalashnikov (1998) investigated drag reduction using high molecular weight polyethylene oxide as a DRA in rotating outer cylinder geometry and dimensionless representation of friction coefficient was achieved. However, the annular gap in the setup was significantly small which leads to high shear stress and subsequent shear degradation of polymer in the fluid. Further, the gap between the end plates of outer and inner cylinder was similar to annular gap between cylinders, indicating that there was significant contribution of the torque coming from end effects or this gap (between the end plates of outer and inner cylinder) which is not relevant for the study. In the present study, moderately high annular gap was used, to minimize the shear stress acting on polymer chains. In addition, larger gap (> annular gap) between the end plates was provided to make sure that only annular gap generated the torque. Koeltzsch et al. (2003) studied drag reduction using surfactants in a TC setup with a rotating outer cylinder rheometer and for the first time the effect of changing viscosity with varying shear stress was taken into account. However, the highest Re achieved was 30,000 in this study, which doesn't provide much insight on DR which demonstrates significant results at higher Re . Dutcher & Muller (2009) explored the effect of drag reducing agents on flow states in TC system at a wide range of Re_o and Re_i . Eskin (2014) numerically verified the applicability of the TC setup for drag reduction characterization and recommended a radius ratio to be less than 0.5 for this purpose. The current study utilizes different parameters ($\eta = 0.76$ and $\Gamma = 10.57$) for examining drag reduction which to the best of our knowledge have not been tested before. Initial validation tests were conducted with water for dimensionless torque and Reynolds number similar to pre-existing studies. Drag reduction at four different DRA concentrations was then explored

and compared with literature.

METHODS

A TC set-up (Figure 1) with a static outer cylinder and a rotating inner cylinder was designed with the following parameters: $r_i = 6.0325$ cm, $r_o = 7.9375$ cm, $L = 15$ cm, $\eta = 0.76$, $\Gamma = 7.89$, $d = 1.9$ cm. There were three major components of this system: i) TC Chamber ii) DC Motor and iii) Torque Sensor.

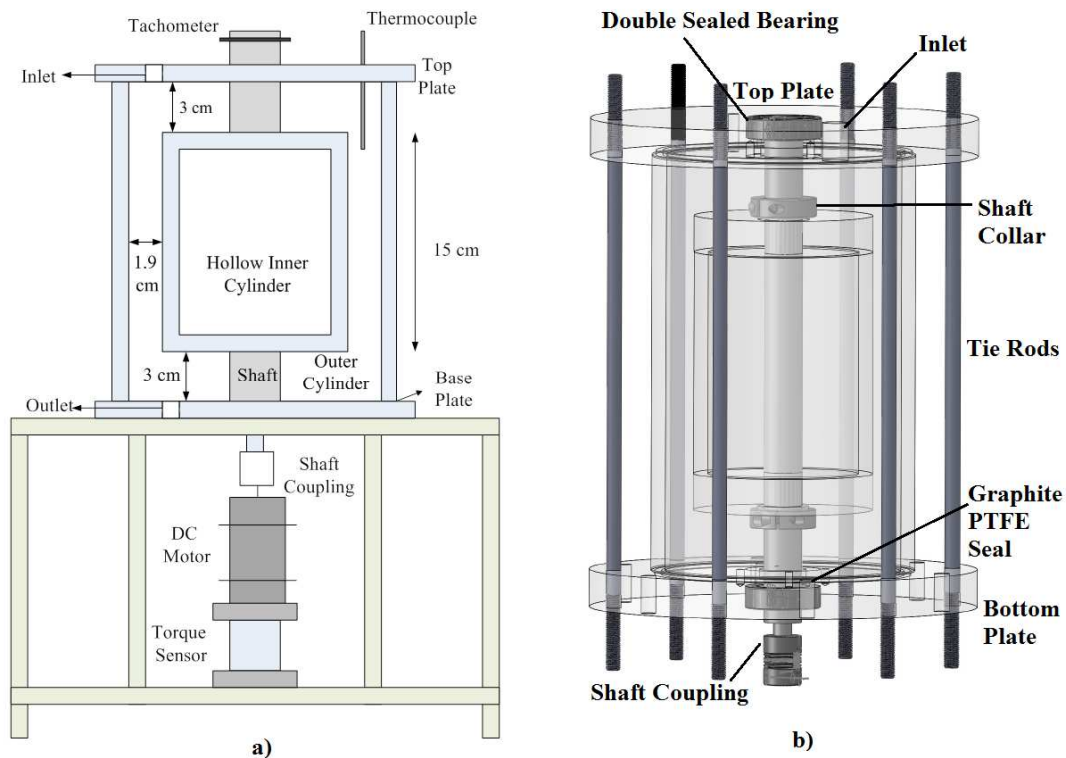


Figure 1: a) Schematics of the Taylor-Couette Setup Used in the Current Study, and b) Solidwork Model of the Concentric Cylinders of the Setup Connected using Tie Rod

The main TC Chamber consisted of two concentric cylinders which were fabricated using acrylic thereby allowing flow visualization in the annular gap. A 3 cm gap between the end plates of two cylinders was deliberately provided in order to minimize the end effects. In case of smaller aspect ratio (< 10), significant end effect can be observed due to Ekman circulation (Burin et al., 2006). It arises due to no slip boundary condition at the ends because of which pressure forces are not centrifugally balanced leading to fluid movement in the radial direction. Some setups utilize intermediary rotating end rings in order to overcome this limitation (Hollerbach & Fournier 2005; Altmeyer et al. 2010). In the present setup, a gap ($>$ annular gap) was provided between the end plates of inner and outer cylinder (Figure 1) to overpower the end effects. Further, smaller d ensured that effectively annular gap generated all the torque. Double sealed stainless steel bearings were used at the top and bottom plate of the outer cylinders. Graphite PTFE seals were selected due to their lower coefficient of friction and good wear resistance. A hollow Inner cylinder was fixed to an aluminium shaft and the upper portion (Figure 1 b) of the set-up was connected using tie rods.

A 120V AC, NEMA 34, 1/3 hp speed control DC Motor (Amatek Inc.) was utilized with a speed range from 300-3450 RPM. In the current study, a maximum speed of 2100 RPM was used which created a corresponding Reynolds number of 283,157.

A reaction Torque Sensor (TFF425, *Futek Advanced Sensor Technology, Inc.*) was used for measuring the torque which was connected to the base of motor as shown in Figure 1. The torque sensor had a capacity of 7 N-m with torsional stiffness of 501 N-m/rad. It provided a rated output of 2mV/V. The hysteresis of the torque sensor was less than $\pm 0.2\%$ of the rated output and the system was calibrated by Futek Advanced Sensor Technology, Inc. at 5 different points between 0-7 N-m for both the clockwise and the anti-clockwise direction. A maximum system error was found to be 0.02% of rated output in the clockwise direction whereas -0.03% of rated output in the anti-clockwise direction. A USB220 kit was used to digitize the analog output voltage of the sensor and had a sampling rate of up to 4800 Hz. SENSIT Test and Measurement software was used for recording the torque while testing. A thermocouple was installed at the top plate for tracking the temperature changes and an optical tachometer was set up on the shaft for recording the angular velocity.

Initial experiments were conducted with water at eleven different angular velocities ranging from 600 RPM to 2100 RPM for a Reynolds number span of 8.1×10^4 to 2.83×10^5 . Torque was measured in the chamber with air only to account for friction due to bearings. This measurement was done before and after each test which was found to be constant and was subtracted from the final readings taken with liquid. Polyacrylamide (Magnaflow 5250, *BASF*) was used in the experiments as a drag reducing agent (DRA). It is a high molecular weight (10-25 million Dalton) polyacrylamide flocculant supplied as a free flowing granular powder. Four different concentrations 80, 120, 160 and 200 PPM were employed in this study. DRA solution was prepared by dissolving the polymer in water for 2 hours at 200 rpm using magnetic stirrer and a separate solution was used for each measurement. The viscosity of the polymeric (DRA) solutions was measured using a Rheometer (Anton Paar, *RheolabQC*). In order to verify the effect of shear degradation of the polymer (due to stirring) on drag reduction, 120 ppm DRA solution was stirred for eight different time periods. Degradation of polyacrylamide due to high shear stress has also been reported in the literature (Abdel-Alim et al. 1973) and hence a small study was conducted in which solution was examined in the TC chamber for 80 minutes and torque was measured at different time periods. Temperature was monitored before and after every reading. Even for the highest speed, significant increase in the temperature was not detected and temperature variation was found to be less than $\pm 1^\circ\text{C}$.

RESULTS AND DISCUSSIONS

Torque Scaling

Dimensionless Torque ($G = T / (L\rho v^2)$) was used to scale the torque and was compared with the previous literature (Figure 2). Experimental setup utilized in Lewis & Swinney (1999) had a $\eta = 0.724$ whereas the current study has a $\eta = 0.76$ justifying the slight deviation of G . We obtained $G = 0.4592 * Re^{1.8568}$ for the present experimental results. Lathrop et al. (1992) did the similar scaling ($G \sim Re^a$) and concluded that the exponent increases from 1.66 to 1.87 beyond Re of 1.3×10^4 validating our results.

Comparing to work of Wendt (1933) who employed four different radius ratio η (0.5, 0.68, 0.85 and 0.935); an insight on effect of radius ratio on G was shown. G was interpolated for $\eta = 0.76$ and was compared vs. Re in Figure 2. G observed in the present setup is in well accordance with the past findings validating the torque measurements of the system. Figure 3 compares the non-dimensional torque at $Re = 100,000$ for several values of η (includes data from other studies as well). The Dashed line indicates the theoretical value of G (Wendt 1933) obtained using

$$G = 0.23 \frac{\eta^{3/2}}{(1-\eta)^{7/4}} Re^{1.7} \quad (11)$$

Where $Re = 100,000$. G values observed in this study falls in line with the theoretical value (Equation 5.11) and with the previous studies conducted on other radius ratios.

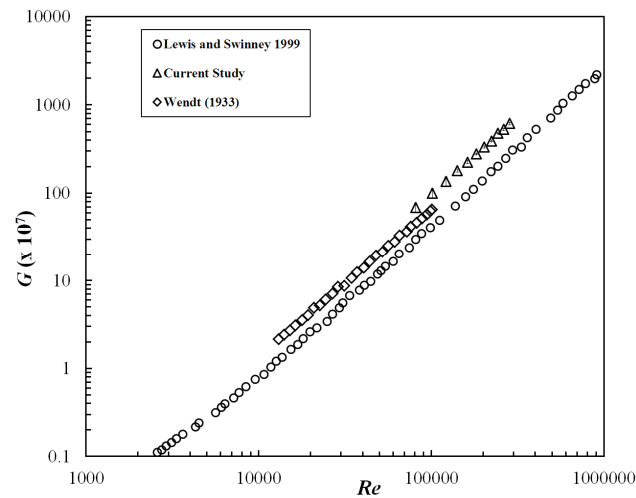


Figure 2: Experimental Values of Dimensionless Torque (G) vs. Reynolds Number (Re) obtained in the Present Study in Comparison to Previous Literature

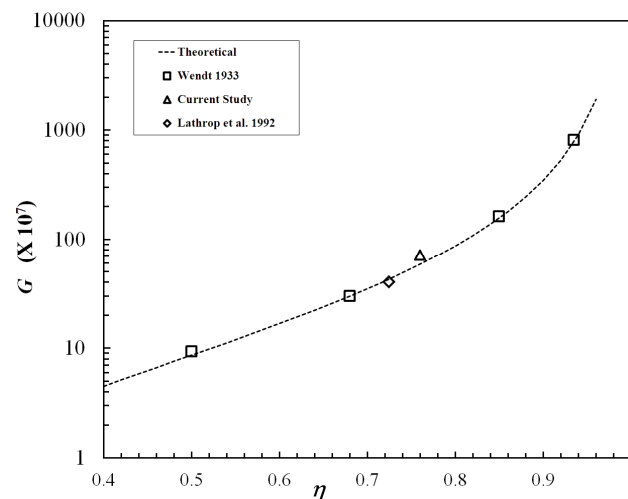


Figure 3: Comparison of Dimensionless Torque (G) for Various Radius Ratios (η) at $Re=100,000$

Comparison with Prandtl-von Kármán Law

As discussed in Introduction, Lathrop et al. (1992) found a similar expression (Equation 10) to *Prandtl von Kármán* Law by considering logarithmic velocity profile in the core of turbulent TC flow. Figure 4 compares the c_f obtained in the current experiments with $Re\sqrt{c_f}$ and a good fit is obtained which is consistent with the above mentioned theory. A linear expression is found with $N=1.1045$ and $M= -1.7141$ (Equation 5.10). This value of N in the Equation 7 yields a value of *von Kármán* constant $\kappa = 0.46$ which is in reasonable agreement with the accepted value of $\kappa = 0.40$.

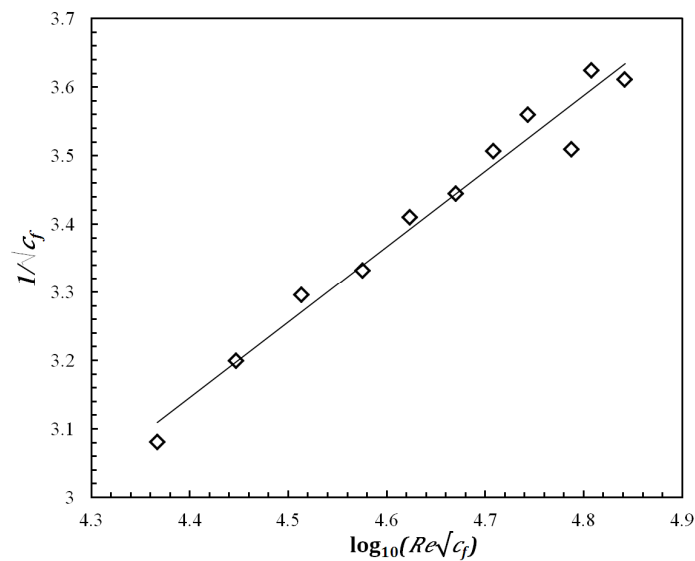


Figure 4: Comparison of Prandtl Von-Kármán Type Skin Friction Law with the Current Experimental Data

Rheological Properties of the Polymer Solution

Shear stress of the DRA solution was measured at different strain rate varying from 1-1000 s⁻¹ and Power law model ($\tau = K \frac{du^n}{dy}$) was used for correlation. Here τ is the shear stress, $\frac{du}{dy}$ is the strain rate, K is a constant and $K \frac{du^{n-1}}{dy}$ is the effective viscosity (μ) of the solution. For Newtonian fluid $n=1$ i.e. viscosity remains constant for various strain rate and for Non Newtonian fluid such as pseudo plastics $n<1$ i.e. viscosity decreases with increasing strain rate. Following are the relations observed for different solution:

$$80 \text{ PPM } \tau = 0.0016 \frac{du}{dy} \text{ (Newtonian Behavior)}$$

$$120 \text{ PPM } \tau = 0.0046 \left(\frac{du}{dy} \right)^{0.781} \text{ (Pseudoplastic-Non Newtonian behavior)}$$

$$160 \text{ PPM } \tau = 0.0061 \left(\frac{du}{dy} \right)^{0.7748} \text{ (Pseudoplastic-Non Newtonian behavior)}$$

$$200 \text{ PPM } \tau = 0.0108 \left(\frac{du}{dy} \right)^{0.707} \text{ (Pseudoplastic-Non Newtonian behavior)}$$

Since the shear rate is variable in the annular gap, viscosity of 120 PPM, 160 PPM and 200 PPM solution is not constant due to non-Newtonian behavior. Hence effect of varying viscosity needs to be taken into account and the following method employed by Koeltzsch et al. (2003) is used. Shear rate for the laminar flow in current geometry is given by (u_ϕ is the azimuthal velocity):

$$\frac{du}{dy} = r \frac{\partial}{\partial r} \left(\frac{u_\phi}{r} \right) = - \frac{2\Omega_i r_i^2 r_o^2}{r^2 (r_o^2 - r_i^2)} \quad (12)$$

Shear rate is highest at the inner cylinder hence further calculation are done at $r=r_i$. Equating μ_{pseudo} and μ_{actual} in case of non-Newtonian at inner cylinder

$$\mu_{actual} \left\{ r \frac{\partial}{\partial r} \left(\frac{u_\varphi}{r} \right) \right\}_{in} = -\mu_{pseudo} \frac{2\Omega_i r_o^2}{(r_o^2 - r_i^2)} \quad (13)$$

$$\frac{\mu_{actual}}{\mu_{pseudo}} = - \frac{\frac{2\Omega_i r_o^2}{(r_o^2 - r_i^2)}}{\left\{ r \frac{\partial}{\partial r} \left(\frac{u_\varphi}{r} \right) \right\}_{in}} \quad (14)$$

Using power law model for non-Newtonian viscosity, the following relation is obtained (as described in Koeltzsch et al. 2003)

$$\left\{ r \frac{\partial}{\partial r} \left(\frac{u_\varphi}{r} \right) \right\}_{in} = \left\{ \frac{1-\eta^2}{n(1-\eta^{2/n})} \right\} \frac{2\Omega_i r_o^2}{(r_o^2 - r_i^2)} \quad (15)$$

$$\frac{\mu_{actual}}{\mu_{pseudo}} = \frac{n(1-\eta^{2/n})}{1-\eta^2} \quad (16)$$

For 120 PPM $\mu_{actual} = 0.933 \mu_{pseudo}$, for 160 PPM $\mu_{actual} = 0.931 \mu_{pseudo}$ and whereas for 200 PPM $\mu_{actual} = 0.904 \mu_{pseudo}$. Since viscosity is used in calculating the Re , corrected Re near the inner cylinder will be 6.7% higher.

A second rheology test was conducted by varying strain rate from 1-1000 s^{-1} . Constant viscosity (known as μ_{inf} according to Carreau Model) was obtained after a strain rate of 800 s^{-1} . Since in our study the strain rate is much higher than 800 s^{-1} , μ_{inf} will be used to calculate the Re . Table 1 lists μ_{inf} and ρ for various DRA solutions used in this study.

Table 1: Density and Dynamic Viscosity of DRA Solutions Used in the Study

| DRA Concentration | Density ρ (kg/m ³) | Dynamic Viscosity μ_{inf} (Pa.s) |
|-------------------|-------------------------------------|--------------------------------------|
| 80 PPM | 984.66 | 1.28 X 10 ⁻³ |
| 120 PPM | 977 | 1.34 X 10 ⁻³ |
| 160 PPM | 962.66 | 1.94 X 10 ⁻³ |
| 200 PPM | 958.66 | 2.16 X 10 ⁻³ |

Drag Reduction using Polymers

Figure 5 shows the skin friction coefficient (c_f) vs. Re for water (as a reference case) and drag reducing solutions at several polymeric concentrations. Only the turbulent regime is shown in the plots where skin friction coefficient of water is found to scale well with $c_f \propto Re^{-1/4}$. Virk et al. (1967) witnessed the onset of drag reduction and observed that there is a critical value of Re required to realize the DR. When this condition is met, the polymer chains are elongated and demonstrate enhanced elongational viscosity (Lumley 1973). This substantial increase in viscosity, combined with the interaction of these stretched chains with vortices dampens the turbulence. This onset was observed for 80 PPM DRA solution and critical value of Re for this solution was found here to be 70,000. With increasing DRA concentration, there is a decrease in this critical value of Re , and since the experiments were not conducted below $Re=50,000$ (due to setup limitation), this onset wasn't observed for other DRA solutions. Furthermore it can be observed from the plot, that all the DRA solutions show a smaller value of skin friction coefficient in comparison to water. Similar observations were reported by Koeltzsch et al. (2003), for drag reduction using surfactant and by Kalashnikov (1998), for drag reduction using high molecular weight polyethylene oxide (2-100 PPM) in a TC Set up. Kalashnikov (1998), similar to the present study, observed a threshold value of Re for DR and found it to be related to a transition from inertial to inertial-elastic turbulence. It was postulated in their study that a critical value of Weissenberg number (ratio of viscous forces to elastic forces) is

required for this transition, which occurs at a threshold wall shear stress (which scales with threshold Re). Once the critical value of Weissenberg number is achieved, coil-stretch transition of the polymer chains occurs, which facilitates in dampening the turbulent structures (Sreenivasan & White, 2000). Turbulent drag reduction has been observed as a boundary layer effect with an increase in the buffer layer thickness, which has been noticed after the drag reduction. Hence, an increase in the slope (c_f vs Re) after the addition of DRA was observed in the current study, and is in good agreement with the literature (Kalashnikov 1998; Sreenivasan & White, 2000; White et al., 2004).

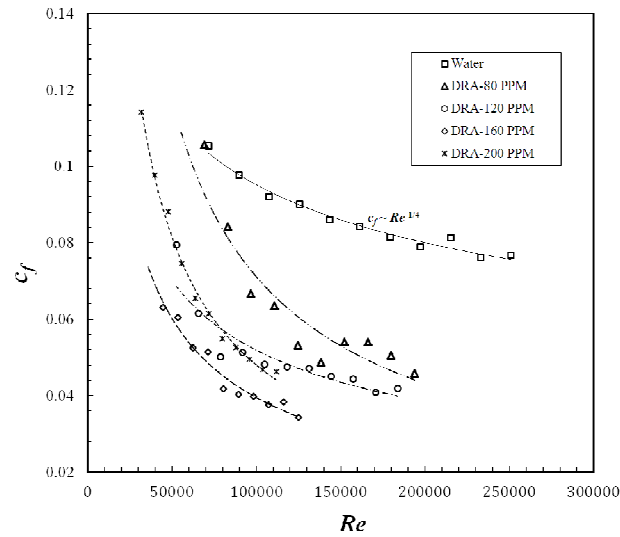


Figure 5: Skin Friction Coefficient (c_f) vs Reynolds Number (Re) for Water and Drag Reducing Solution at Various Polymeric Concentrations

In order to understand the drag reduction, a different plot (Figure 6) is chosen in which Drag Reduction ($DR\%$) is expressed by Equation 17, where $c_{f,w}$ is the skin friction coefficient of water and $c_{f,s}$ is the skin friction coefficient of DRA solution.

$$DR\% = \frac{c_{f,w} - c_{f,s}}{c_{f,w}} \times 100 \quad (17)$$

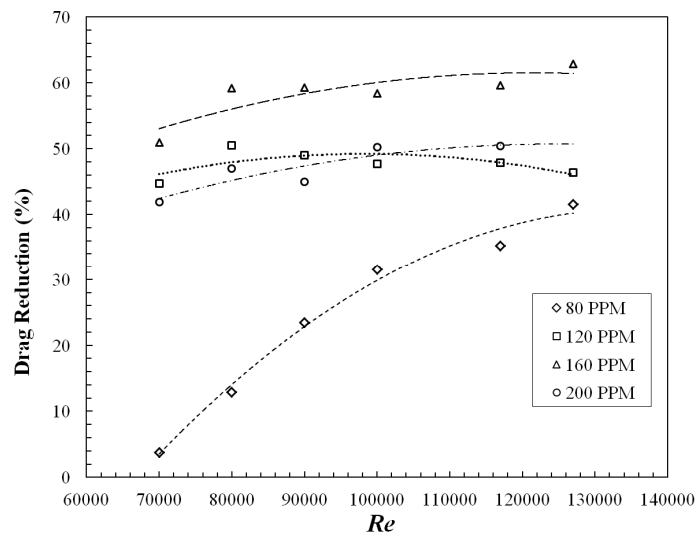


Figure 6: Drag Reduction (%) vs Re for Different Concentrations of DRA Solution

Results from Figure 5 were used to obtain the plots in Figure 6. For the 80 PPM DRA solution, it is evident that there is an increase in $DR\%$ with increasing Re . It is in good agreement with the results reported by Virk et al. (1967). With an increase in Re , there is an increase in wall shear stress which improves the stretching of polymer chains, resulting in higher DR. Further it can be observed that with an increase in concentration, there is an increase in $DR\%$ up to 160 PPM, beyond which there is a decrease in drag reduction. This increase in DR with the increase in concentration is due to increased interaction of polymers with turbulent structures and is in accordance with the observations of Bewersdorff (1982) and, Sa Pereira & Pinho (1994) in pipe flow. A decrease in DR beyond 160 PPM could be attributed to increased entanglements of polymer chains amongst themselves, leading to reduced mobility of the polymer chains and is in agreement with the observations made by Fernandes et al. (2009). Further, $DR\%$ increases slightly with Re for 160 PPM solution however it was found to be constant for 120 PPM and 200 PPM solution. These solutions (120PPM, 160 PPM and 200 PPM) demonstrate the asymptotic value of DR i.e. 47%, 63% and 50% respectively. This is similar to the findings of Virk et al. (1967) who also observed a Maximum Drag Reduction (MDR)

Asymptote, which was independent of pipe size and type of polymer used (Virk & Merrill, 1969). In summary, all the observations made in this study were in agreement with the previous studies on pipe and channel flow validating that the TC setup is an excellent tool for drag reduction testing.

Some experiments were conducted for 120 PPM DRA solution at $Re=1.8 \times 10^5$ for a longer time (80 min) period in order to see if the shear rate deteriorated the polymer chains and in turn could affect the DR, however, torque (similarly DR) was found to be unchanged with time.

Since the DRA solution was prepared by mixing the polymer in water using a magnetic stirrer, a brief study was conducted to examine the effect of the stirring time of the polymer in water on $DR\%$ (for 120 PPM DRA solution) at $Re=1.8 \times 10^5$. Stirring time was found to have significant effect on $DR\%$. Shorter stirring time (1000s) and longer stirring time (100000s) lead to decrease in $DR\%$. 1000s was observed to be insufficient for the polymer to completely dissolve in water, whereas 100000s is considerably long for the polymer chains to dissolve leading to deterioration of the polymer chains.

CONCLUSIONS

Drag reduction in turbulent pipe flow using high molecular weight polymer as additives, known as drag reducing agents (DRA), is a well-recognized field and has been an area of extensive research. However, a significant amount of polymer is utilized to test the polymers for drag reduction at lab scale, using pipe flow or a channel flow setup. In the current study, a Taylor Couette flow apparatus was designed and tested for drag reduction using high molecular weight polymers. The setup consisted of a stationary outer cylinder and rotating inner cylinder, where drag (skin friction coefficient) was inferred from torque acting on inner cylinder. Initial experiments were conducted with water in which torque was scaled using dimensionless torque (G) and Reynolds number (Re). The results obtained were compared with the previous literature and were found to be in good agreement. The effect of the changing molecular viscosity of the polymeric solution with varying shear rate was discussed. It can cause a difference of 6.7% in the measurement of Re across the inner and outer wall. However, beyond particular strain rate, a constant viscosity (μ_{inf}) of the polymeric solution is obtained. In the present study, Re was deliberately chosen to be high enough that it surpassed the strain rate to achieve μ_{inf} and μ_{inf} was used to calculate Re . Further, drag reduction was measured for four different concentrations of

polymeric/DRA solution. An increase in DR% was observed for increase in concentration and Re . An onset of drag reduction was observed for 80 PPM DRA solution at $Re=70,000$ and Maximum Drag Reduction (MDR) or the Virk asymptote of 63% DR was observed for 160 PPM DRA solution. The effect of stirring time of the polymer solution was found to have a profound effect on DR and longer stirring time was found to decrease the DR% (attributed to polymer chain breakage).

In summary, the TC setup is a powerful tool to assess the drag reduction with an important advantage being its small geometry. In addition, it is quick to use and requires smaller solution volumes. This provides an excellent platform for evaluating a wider range of DRA solutions.

ACKNOWLEDGEMENTS

Authors would like to thank Natural Science and Engineering Research Counsel of Canada for funding this work.

REFERENCES

1. Abdel-Alim, a. H., & Hamielec, a. E. (1973). Shear degradation of water-soluble polymers. I. Degradation of polyacrylamide in a high-shear couette viscometer. *Journal of Applied Polymer Science*, 17(12), 3769–3778. <http://doi.org/10.1002/app.1973.070171218>
2. Abshagen, J., Schulz, A., & Pfister, G. (1997). The Couette-Taylor Flow : A Paradigmatic System for Instabilities, Pattern Formation and Routes to Chaos. *Nonlinear Physics of Complex Systems*, 476, 63–72.
3. Altmeyer, S., Hoffmann, C., Heise, M., Abshagen, J., Pinter, a., Lücke, M., & Pfister, G. (2010). End wall effects on the transitions between Taylor vortices and spiral vortices. *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics*, 81(6), 1–9. <http://doi.org/10.1103/PhysRevE.81.066313>
4. Bewersdorff, H.W., (1982)Effect of Centrally Injected Polymer Thread on Drag in Pipe Flow, *Rheol Acta.*, 21: 587-589.
5. Burin, M. J., Ji, H., Schartman, E., Cutler, R., Heitzenroeder, P., Liu, W., Raftopolous, S. (2006). Reduction of Ekman circulation within Taylor-Couette flow. *Experiments in Fluids*, 40(6), 962–966. <http://doi.org/10.1007/s00348-006-0132-y>
6. Cole, J. a. (1976). Taylor-vortex instability and annulus-length effects. *Journal of Fluid Mechanics*, 75(01), 1. <http://doi.org/10.1017/S0022112076000098>
7. Couette, M. M. (1890). Études sur le frottement des liquids. *Ann. Chim. Phys.* 6, Ser. 21, 433-510, 1890.
8. Davey, a. (1962). The growth of Taylor vortices in flow between rotating cylinders. *Journal of Fluid Mechanics*, 14(03), 336. <http://doi.org/10.1017/S0022112062001287>
9. Di Prima, R. C., & Swinney, H. (1985). Instabilities and transition in flow between concentric rotating cylinders. In
10. Dutcher, C. S., & Muller, S. J. (2009). The effects of drag reducing polymers on flow stability : Insights from the Taylor-Couette problem. *Korea-Australia Rheology Journal*, 21(4), 223–233.
11. Eskin, D. (2014). Applicability of a Taylor–Couette device to characterization of turbulent drag reduction in a pipeline. *Chemical Engineering Science*, 116, 275–283. <http://doi.org/10.1016/j.ces.2014.05.016>
12. Fernandes, R. L. J., Fleck, B. a., Heidrick, T. R., Torres, L., & Rodriguez, M. G. (2009). Experimental Study of DRA for Vertical Two-Phase Annular Flow. *Journal of Energy Resources Technology*, 131(2), 023002. <http://doi.org/10.1115/1.3120299>
13. Hershey, H. C., & Zakin, J. L. (1967). EXISTENCEOFTWOTYPESOFDRAG REDUCTION IN PIPE FLOW OFDILUTE POLYMERSOLUTIONS. *I&EC Fundamentals*, 6(August), 381–387.

14. Hollerbach, R., & Fournier, A. (2005). End-effects in rapidly rotating cylindrical Taylor-Couette flow, 114–121. <http://doi.org/10.1063/1.1832141>
15. Huisman, S. G., Scharnowski, S., Cierpka, C., Kähler, C. J., Lohse, D., & Sun, C. (2013). Logarithmic Boundary Layers in Strong Taylor-Couette Turbulence. *Physical Review Letters*, 110(26), 264501. <http://doi.org/10.1103/PhysRevLett.110.264501>
16. Kalashnikov, V. N. (1998). Dynamical similarity and dimensionless relations for turbulent drag reduction by polymer additives. *Journal of Non-Newtonian Fluid Mechanics*, 75(2-3), 209–230. [http://doi.org/10.1016/S0377-0257\(97\)00093-1](http://doi.org/10.1016/S0377-0257(97)00093-1)
17. Koeltzsch, K., Qi, Y., Brodkey, R. S., & Zakin, J. L. (2003). Drag reduction using surfactants in a rotating cylinder geometry. *Experiments in Fluids*, 34(4), 515–530. <http://doi.org/10.1007/s00348-003-0590-4>
18. Lathrop, D. P., Fineberg, J., & Swinney, H. L. (1992). Transition to shear-driven turbulence in Couette-Taylor flow. *Physical Review A*, 46(10), 6390–6405. Retrieved from <http://link.aps.org/doi/10.1103/PhysRevA.46.6390>
19. Lathrop, D. P., Fineberg, J., & Swinney, H. L. (1992). Turbulent-Flow between Concentric Rotating Cylinders At Large Reynolds-Number. *Physical Review Letters*, 68(10), 1515–1518. Retrieved from http://apps.isiknowledge.com/InboundService.do?product=WOS&action=retrieve&SrcApp=Papers&UT=A1992HG6800019&SID=2Df6ajHCg4aC@Ij3KiI&Init=Yes&SrcAuth=mekentosj&mode=FullRecord&customersID=mekentosj&DestFail=http://access.isiprproducts.com/custom_images/wok_f
20. Lewis, G. S., & Swinney, H. L. (1999). Velocity structure functions, scaling, and transitions in high-Reynolds-number Couette-Taylor flow. *Physical Review. E, Statistical Physics, Plasmas, Fluids, and Related Interdisciplinary Topics*, 59(5 Pt B), 5457–5467. <http://doi.org/10.1103/PhysRevE.59.5457>
21. Lumley, J. L. (1969). Drag Reduction by Additives. *Annual Review of Fluid Mechanics*. <http://doi.org/10.1146/annurev.fl.01.010169.002055>
22. Lumley, J.L., (1973) Drag reduction in turbulent flow by polymer additives. *J. Polymer Sci., Macromol. Rev.* 7, 263-290.
23. Merbold, S., & Egbers, C. (2012). Analysis of differentially rotating turbulent Taylor-Couette-flow using Laser Doppler Anemometry and comparison with torque measurements, 9–12. Ptasinski, P. K., Nieuwstadt, F. T. M., Van Den Brule, B. H. A. A., & Hulsen, M. A. (2001). Experiments in Turbulent Pipe Flow with Polymer Additives at Maximum Drag Reduction. *Flow, Turbulence and Combustion*, 66(2), 159–182. <http://doi.org/10.1023/A:1017985826227>
24. Sá Pereira, A. and Pinho, F.T., (1994) Turbulent Pipe Flow Characteristics of Low Molecular Weight Polymer Solutions, *J. Non-Newtonian Fluid Mech.*, 55, pp. 321-344,
25. Sreenivasan, K. R., & White, C. M. (2000). The onset of Drag Reduction by Dilute Polymer additives. *Journal of Fluid Mechanics*, 409, 149–164.
26. Panton, R. L. (1992). Scaling laws for the angular momentum of a completely turbulent Couette flow. *Comptes Rendus de l'Académie Des Sciences. Série 2, Mécanique, Physique, Chimie, Sciences de L'univers, Sciences de La Terre*, 315(12), 1467–1473. Retrieved from <http://cat.inist.fr/?aModele=afficheN&cpsidt=4446796>
27. Poncet, S., Da Soghe, R., Bianchini, C., Viazzo, S., & Aubert, A. (2013). Turbulent Couette-Taylor flows with endwall effects: A numerical benchmark. *International Journal of Heat and Fluid Flow*, 44, 229–238. <http://doi.org/10.1016/j.ijheatfluidflow.2013.05.018>
28. Ptasinski, P. K., Nieuwstadt, F. T. M., Van Den Brule, B. H. A. A., & Hulsen, M. A. (2001). Experiments in Turbulent Pipe Flow with Polymer Additives at Maximum Drag Reduction. *Flow, Turbulence and Combustion*, 66(2), 159–182.

<http://doi.org/10.1023/A:1017985826227>

29. Taylor, G. I. (1923). *Stability of a Viscous Liquid Contained between Two Rotating Cylinders*. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*. <http://doi.org/10.1098/rsta.1923.0008>
30. Toms, B.A., *Some observations on the flow of linear polymer solutions through straight tubes at large Reynolds numbers*. In: *Proceedings 1st International Congress on Rheology*. North Holland, Amsterdam pp. 135–141 (1949).
31. Van Gils, D. P. M., Huisman, S. G., Bruggert, G. W., Sun, C., & Lohse, D. (2011). *Torque scaling in turbulent Taylor-Couette flow with co- and counterrotating cylinders*. *Physical Review Letters*, 106(2), 1–4. <http://doi.org/10.1103/PhysRevLett.106.024502>
32. Virk, P.S., Merrill, E.W., 1969. In: Wells, C.S. (Ed.), *The Onset of Dilute Polymer Solution Phenomena in Viscous Drag Reduction: Viscous Drag Reduction*. Plenum Press, New York.
33. Virk, P.S., Merrill, E.W., Mickley, H.S., Smith, K.A., Mollo-Christensen, E.L., 1967. *The Toms phenomenon: turbulent pipe flow of dilute polymer solutions*. *Journal of Fluid Mechanics* 30, 305–328.
34. Wendt, F. (1933). *Turbulente Strömungen zwischen zwei rotierenden konaxialen Zylindern*. *Ingenieur-Archiv*, 4(6), 577–595. <http://doi.org/10.1007/BF02084936>
35. White, C. M., Somandepalli, V. S. R., & Mungal, M. G. (2004). *The turbulence structure of drag-reduced boundary layer flow*. *Experiments in Fluids*, 36(1), 62–69. <http://doi.org/10.1007/s00348-003-0630-0>
36. Yi, M.-K., & Kim, C. (1997). *Experimental studies on the Taylor instability of dilute polymer solutions*. *Journal of Non-Newtonian Fluid Mechanics*, 72(2-3), 113–139. [http://doi.org/10.1016/S0377-0257\(97\)00032-3](http://doi.org/10.1016/S0377-0257(97)00032-3)

